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Quality and quantity of leachate with different ages and operations in semi-arid climate

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ABSTRACT

This study investigates the landfill leachate generated from three landfills with different ages and operations in a semi-arid climate and assesses major differences in qualitative and quantitative leachate characteristics compared with other landfills located in different areas with similar climatic conditions and economic situation. These sites are called, Marrakesh (new controlled and closed) and the Greater Agadir controlled landfills, respectively (MNL, MCL and GAL). The waste composition showed that the organic matter fraction was characterized by high water content and was generally the dominant fraction in Marrakesh and Agadir landfill sites with values of 68.4% and 70.23% by weight, respectively. The average values of the physicochemical parameters were recorded. The annual leachate volumes generated from the three landfill sites were determined by the water balance method. Beside the age of the landfill, the obtained results indicate that leachate quality and quantity were highly dependent on the composition of the municipal solid waste (MSW) arriving at these landfill sites, underlying conditions, types of leachate and leachate flow in MSW. It was also concluded that leachate is still generated in landfills located in a semi-arid area even with a low annual precipitation, due to the high moisture content of MSW.

Keywords: Landfill leachate; Semi-arid climate; Waste composition; Water balance; Leachate flow; Developing countries

1. Introduction

In Morocco, the demographic expansion, rapid industrialization, changes in production modes and consumption patterns have caused a substantial increase in the amount and diversity of solid wastes ranging from synthetic to biodegradable material [1]. Actually, over 6 million ton/year of solid waste is generated daily in Morocco [2]. This amount is expected to rise over the next few years due to the rising population and the development of the country.

Landfilling is the most common method for municipal solid waste (MSW) disposal currently being applied in many parts of the world, especially in developing countries where it is still an inherently prevalent solution [3]. Further, the simplicity and economic advantages of landfilling in terms of technical operating parameters, environmental conditions

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and socio-economic aspects make it the disposal solution of choice in many instances compared with other solid waste management techniques, such as biological composting, gasification and incineration [3,4]. However, one of the drawbacks of this disposal technique is the production of highly contaminated leachate [5]. In Morocco, most landfills are usually open dumps/unlined landfills [1]. Only a few of them which have been constructed within the scope of the National Household Solid Waste Program (NHSWP) launched in 2007 by the Moroccan Ministry of Interior and the Moroccan Secretary of State for Water and Sustainable Development, with the support of the World Bank, can be regarded as controlled landfills. These types of landfills were designed and constructed according to engineering specifications.

Landfill leachate is a liquid by-product of decomposition in landfills that seeps through or out of waste deposits in landfill sites [6]. Landfill leachate varies widely depending on the waste type and the waste age [7]. The formation of the leachate occurs principally when the percolating effluent dissolves the soluble components out of the deposited waste [8].

Generally, leachates generated in municipal landfill may contain a plethora of organic contaminants measured as chemical oxygen demand (COD), biochemical oxygen demand (BOD), ammonia, monoaromatic hydrocarbons, significant amounts of heavy metals, phenols, pesticides and inorganic salts. All these chemicals are a great threat to the surrounding soil, groundwater and even surface water, thereby posing severe pollution to receiving water bodies [9]. Generally, the risks of the leachate on the natural environment and human health are evaluated by comparing leachate quality with Moroccan standards.

Landfill leachate treatment has been a serious problem for several years in developing countries, and has to meet stringent environmental regulations. Generally, successful and cost-effective leachate methods are difficult to find [10]. A typical landfill leachate management in developing countries displays an array of problems including lack of knowledge of treatment systems by authorities, compliance problems with discharge limits, highly polluted landfill leachate and the selection of inadequate leachate treatment options.

Currently, many leachate treatment processes have been used in Morocco, including among others, physical, chemical, biological and combined processes. Among these processes, the most commonly used are natural evaporation, coagulation–flocculation and reverse osmosis [11]. Over the last decades, in many developed countries, advanced and new landfill treatment methods have received significant interests which offer better removal of contaminants, among which advanced oxidation and bioremediation processes [12]. Despite their proven efficiency, these treatment methods did not yield satisfactory results. This could be explained by the variability in the quantity and quality of leachate over the life span of the treatment plant [13].

In addition, the estimate of the leachate quantity is required in designing landfill and can affect operating costs for leachate collection and treatment [14]. This leachate quantity is determined by a number of methods based on empirical methods such as the Hydrologic Evaluation of Landfill Performance (HELP) computer model [15] and the water balance method which was developed by the US Environmental Protection Agency (EPA) [16]. The majority of these methods were developed for humid climates and based on the theoretical concept which states that the refuse will not produce leachate until it has reached filled capacity. However, the concept, as mentioned here, is obviously a gross oversimplification [17]. Such an approach ignores occasional precipitation, as well as the existence of preferential flow which occurs in macropores [18]. Thus, the water balance model should be applied considering the local climate conditions in which the landfill is situated.

In an attempt to make up for this data gap on leachate quality and quantity variations, many studies have been conducted to investigate the quantity of landfill leachate using the water balance method adapted for application in semi-arid climate [18,19]. However, a comparison of leachate quality and quantity of all types of leachate (i.e., young, intermediate, old) under semi-arid climate from three landfill sites with different ages and waste types, taking into consideration the effect of the MSW composition is missing from the literature.

Therefore, this study focused on assessing the variations in leachate quantity and quality with landfill age, leachate types and municipal waste composition under semi-arid climate. Additionally, this study aims to determine the composition of MSW arriving at these landfill sites and points out its important effect on leachate quality and quantity.

2. Materials and methods

2.1. Site description

This study was conducted in Morocco in three different landfills located in Marrakesh city, Al Mnabha village and Agadir city (Fig. 1), which were selected to be representative of landfills of different ages and type of waste.

2.1.1. Marrakesh new controlled landfill

The new controlled disposal site of Marrakesh is an intercommunal landfill, which is located in Al Mnabha village at 35 km away from the northern portion of Marrakesh (Fig. 1). The site extends over an area of 182 ha and has recently started to operate in 2016. Initially, the first 10.35 ha cell (of which 3 ha comprises the completed landfill) was constructed, with a maximum fill height of 16 m. The site is currently active and permitted to receive MSW only of approximately 900 to 1,000 ton/d. In addition to landfilling operations, the site also accommodates a composting plant and waste recovery center, with a treatment capacity of 421,000 metric tons a year, which is expected to reach 702,500 metric tons by 2028. This intercommunal landfill serves a large region covering 13 municipalities (hereafter called The Marrakesh area). The landfill is lined and there are two leachate collection ponds, with a total storage capacity of 56,000 m^3, located at the edge of the landfill. The collected leachate is also treated in the ponds using natural evaporation process until completion of the reverse osmosis leachates treatment plant.

2.1.2. Marrakesh closed landfill

Marrakesh landfill site spreads over an area of approximately 9 ha, it is situated 15 km in the northern part of the city and on the Eastern bank of Tensift river. The site is reached via the main road RP 9 leading to the city of Safi (Fig. 1). This landfill is a non-engineered municipal waste disposal, opened in 1980 and was recently closed in 2016. This site is currently under reclamation and re-planting operations. The landfill received an average of approximately 703 tons of waste/d [20] from the city of Marrakesh and surrounding areas. The waste disposed at Marrakesh site included, among others, municipal solid, demolition, commercial and industrial waste. The landfill can produce up to 60 m^3 each day of leachate. Leachate generated drains out by gravity and flows into three leachate collection pools located behind the landfill without any facilities of treatment.

2.1.3. Greater Agadir controlled landfill

The site of the Greater Agadir is operated by a private contractor as controlled landfill with an area of 41 ha, which is currently in use. The new landfill is located in the west of Tamellast village between the hills of high Atlas and the western plain of Souss, 6 km from the north-eastern part of the city, and 4.5 km from the old waste disposal site called Bikarrane (Fig. 1). The landfill began operating in 2010 subsequent to the completion of the first cell in order to receive MSW from approximately 800,000 inhabitants [21]. The site accepts an average of 756 tons of waste per day and serves 10 municipalities composing the Greater Agadir. The landfill is equipped with a leachate collection system, which is still in use but requires extensive maintenance. The leachate seeps out of the landfill and is collected in three lined ponds which provide total storage of 68,000 m^3. The leachate is then treated in the ponds by natural evaporation [2].

2.2. Sampling procedure

2.2.1. Leachate sampling

The leachate raw samples were collected from the three above-mentioned landfill sites with different ages, waste composition, geographic setting, leachate production and landfilling technology on the same period between February and March 2016.

As described by Christensen et al. [22], the three landfills were sampled directly from the leachate collection pond and from the leachate collection drains, thus there is no dilution with groundwater or surface water. Two grab leachate samples were taken from the main collecting drains with the first one from the leachate collection drain in medium-aged GAL cell that received MSW from 2012 to 2016. The second one was taken from the other leachate collection drain in young-aged MNL cell that was not yet capped, and had recently started to receive MSW in 2016 and is still currently in use. Additionally, in MCL, composite leachate samples were taken randomly at three points in the unaerated leachate collection pond in order to ensure sample representativeness and homogeneity [23]. Leachate samples were collected in clean polypropylene bottles and transported in a portable ice bag, then preserved in the refrigerator [24].

2.2.2. Sampling and determination of waste sample size

Vehicle loads of waste were designated for sampling, and a sorting sample was collected from the discharged vehicle load. These vehicle loads for sampling were selected randomly from eligible collection routes during each day of the 1-week sampling period, as to be representative of the waste stream. A weekly period is defined as 6 d. The weight of each sorting sample was 91–136 kg and was prepared properly (mixed, coned and quartered) from each discharged MSW vehicle load using a shovel with at least a 1 m^3 bucket.

The number of sorting samples (n) required to achieve the desired precision level (p) is computed by using the following formula (1) [25]:

$$n = \left(\frac{ts}{pz}\right)^2 \tag{1}$$

where t = the student's t statistic corresponding to the desired confidence level, s = estimated standard deviation, z = estimated mean.

2.3. Waste composition analysis and leachate characterization

2.3.1. Sorting procedure and weighing of sorted waste

The samples for sorting were obtained by reducing the sample collected between 91 and 136 kg using a cone and

(a) (b) (c)

Fig. 1. View of the three landfill sites located in Morocco with basins of leachate storage (Google earth, 2017): (a) Marrakesh New controlled landfill (NCL), (b) Marrakesh closed landfill (MCL), and (c) Greater Agadir controlled landfill (GAL).

quartering technique ASTM D 5231-92 [25]. Materials were sorted into six categories for this comparative analysis listed in Table 1, which were selected according to the possibility of recovering the corresponding materials and to the classification of waste composition adopted by the Moroccan Secretary of State for Water and Sustainable Development. The waste to be sorted was spread over a flat and clean floor (3 m × 3.6 m) to ease sorting, segregation and weighing. From the floor, the waste is scooped out and placed over a sorting table using a shovel. Each listed item is sorted and deposited into a 1 m^3 bucket, positioned around the table, by the Laboratory of Ecology and Environment (L2E) research team. The buckets were weighed before and after the sorting using a portable scale placed on level ground. Then each one of the fractions was weighed and the results were recorded on a sampling sheet. The percentage composition of each of the components in the sorting sample was calculated by the weights of the components using this formula:
Percentage composition of waste

$$\frac{\text{Weight of separated waste}}{\text{The total of mixed waste sample}} \times 100 \quad (2)$$

2.3.2. Physicochemical characterization of landfill leachate

Physicochemical analyses of landfill leachate samples were performed at L2E of the Biology Department of the Faculty of Science Semlalia. The collected leachate samples were filtered by Whatman filter paper to remove suspended solids (SS) prior to measurement. The laboratory analytical procedures were conducted according to Standard Method for the Examination of Water and Wastewater [24].

The analyses were performed for each sample in triplicate and the average values were taken. The SS which were removed from the samples by filtration were then weighed according to method (2540 D) [24]. The electrical conductivity and pH were measured by CD-2005 conductivity meter and PH-2006 pH meter, respectively. After oxidation with dichromate, the COD was determined by spectrophotometer (DR/2000 direct reading spectrophotometer) according to Open Reflux Method (220-B) [24], while BOD measurements were performed following the Standards Method (5210) [24]. Total Kjeldahl Nitrogen (TKN) (4,500-Norg C) was measured by Kjeldahl flask digestion followed by distillation and titrimetric method. Distillation (4500-NH3 B) and titrimetric (4500-NH3 C) method was used to analyse NH_4^+–N. The NO_3–N concentration was determined by the Devarda's alloy Reduction Method [26]. The heavy metals concentrations were determined using inductively coupled plasma optical emission spectrometry (ICP-OES). Phenols were extracted and purified with ethyl acetate according to the method described by Macheix et al. [27] then assayed with Folin–Ciocalteu's technique.

Table 1
Description of waste component categories

Waste categories	Waste components
Organic	Food, animal excrements, wood, garden trimmings
Paper-board	Office paper, bills, milk box and juice box, cartons, brown (Kraft) paper bags and egg containers
Plastics	All plastic (PET, HDPE, PVC, LDPE, PP, PS, etc.)
Metals	Ferrous, non-ferrous
Glass	All glass (Containers of solid foods or liquids, etc.)
Other	Nappies/sanitary products, small toys, shoes, cotton, textiles, debris, hair, other waste (small construction waste material)

2.4. Leachate generation and water balance

The amount of leachate generated was estimated on an annual basis along the sampling period 2016 using a simple water-balance model for predicting leachate generation in MSW landfills located in semi-arid areas as proposed by Aljaradin and Persson [18], taking into account the quantities of all liquids entering and leaving the landfill during a specified period.

This annual water balance model presented in this study was adapted for application in two operating landfills, MNL and GAL. The model was applied also to MCL, which is currently under reclamation operations. The approach used here accounts for an annual tipping dimensions and basic local climatological data [28]. The annual leachate generation volume per tipping was obtained by multiplying the leachate flow volume by the tipping area by the average fill depth, taking into account each of the major components of water balances and the refuse conditions (i.e., density of the waste and annual amount of waste received by the landfill).

The algebraic statement of this model is expressed by the annual water balance equation [18] as follows:

$$W_i\left(P + W_{\text{iw}} + W_{\text{gw}} + W_{\text{iw}}\right) = W_0\left(E_p + L + I\right) \quad (3)$$

where P is the precipitation; W_{iw} is the water content of incoming waste; W_{gw} is the inflow of surface and groundwater; W_{iw} is the co-disposal of wastewater; E_p is the evapotranspiration; L is the leachate; and I is infiltrate deep drainage.

Simple evapotranspiration from the daily intermediate and final covers were not taken into account in the water balance calculations, since no vegetation is placed in active landfill layers. With further simplification, the equation gives the annual water balance and becomes as follows:

$$W_i\left(P + W_{\text{iw}} + W_{\text{gw}} + W_{\text{iw}}\right) = W_0\left(E + L + I\right) \quad (4)$$

where E is the evaporation.

In the case where landfills are located in semi-arid areas, such as Marrakesh and Agadir cities, precipitation cannot be considered the major leachate generator [18]. This can be associated to the low precipitations as is depicted in Table 2. Thus, precipitation may be neglected. The co-disposal of wastewater is not allowed into the three landfills concerned by this study, which means that the volume of water

Table 2
Monthly precipitation, 2016[a]

Locations	Monthly precipitation (mm)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Marrakesh	6.1	22.1	31.75	1.27	28.7	0.51	9.91	3.05	3.05	3.05	41.91	22.85
Agadir	0.25	19.81	5.58	0.76	25.4	0	0	0.5	0.25	18.04	66.79	35.06

[a]Monthly precipitation data were obtained from nearby weather stations (http//clima.tiempo.com).

from the co-disposal of wastewater is also negligible. Inflow of groundwater surface is not significant as the groundwater table is relatively far below the soil surface in the three landfill sites [20,21]. Generally, in warm and dry climates with less than 250 mm of precipitation per year, the capillary water evaporates before it is capable of rising to the top of the soil [29], which indicates negligible influence on the accuracy of water balance calculations.

On the other hand, evaporation (*E*) was estimated based on pooled findings from study carried out in four landfills in semi-arid regions over a period of 44 months by Nyhan et al. [30]. These researchers reported that the evaporation values of landfills cover without vegetation were between 86% and 91% of the precipitation. MNL and GAL were constructed according to engineering specifications. Thus, infiltrates deep drainage (*I*) may also be neglected. However, we did not consider infiltrate deep drainage in MCL negligible due to the fact that this landfill was constructed without any bottom liner systems. The infiltrate deep drainage of leachate was estimated based on results from a study that was conducted in an uncontrolled landfill located at El Jadida city in Morocco, which is similar to MCL in terms of landfill operational practices [31]. Chofqi et al. [31] reported that the estimate leakage rate of leachate from old landfill with uncompacted waste to groundwater is ranging approximately between 97 and 194 mm/year.

Based on the simplified water balance equation and accounting for the above assumptions that take into consideration local conditions, the annual water balance equation can be simplified as follows:

$$\left(W_{\text{iw}}\right) = W_0\left(E + L + I\right) \quad \text{For MCL} \tag{5}$$

$$\left(W_{\text{iw}}\right) = W_0\left(E + L\right) \quad \text{For MNL and GAL} \tag{6}$$

With these two further simplifications, water balance equation (Eqs. (5) and (6)), becomes as follows:

$$L = W_{\text{iw}} - \left(E + I\right) \quad \text{For MCL} \tag{7}$$

$$L = W_{\text{iw}} - E \quad \text{For MNL and GAL} \tag{8}$$

The volumetric moisture content of incoming solid waste was experimentally determined. Initially, the percentage moisture (MC) relative to the total weight of MSW samples was determined according to ASTM D3173-87 [32].

In fact, the volumetric moisture content of the sample was determined through equation:

$$\theta_W = \frac{\rho_T}{\rho_W}\text{MC} \tag{9}$$

where ρ_T = bulk density of the landfilled waste and ρ_W = density of water.

The Department of the Environment [33] reported that typical waste densities range from 650 to 850 kg/m^3. Therefore, the volumetric moisture values can be estimated assuming density of the waste at MNL, MCL and GAL sites to be in the above-mentioned range.

3. Results and discussion

3.1. Number of samples determination

The number of sorting samples in each site of the present study was calculated according to ASTM D5231-92 [25], by using Eq. (1) stated in the previous section. This number of samples is computed well by taking into consideration a 95% confidence level and assuming food waste as the governing waste stream component. It was observed that roughly two-thirds by weight of all MSW entering the landfills was comprised of food waste, which mean that standard deviation (*s*) equals 0.03 and estimated mean (*z*) equals to 0.10, in addition a 10% of precision (*p*) is desired.

Therefore, 37 to 38 samples were needed to be sorted in each site, thus 6 to 7 samples were sorted each day for each site.

3.2. Waste composition analysis

In this study, organic accounted for the largest portion of MSW by weight with 68.4% and 70.23%, respectively, in both Marrakesh area and the Greater Agadir as shown in Table 3. Indeed, organics were the largest component that included mainly food wastes. This is a remarkable result, which could be due to changes in modes of production and consumption patterns and to the substantial increase in tourism industry in Morocco, especially in Marrakesh and Agadir cities where the tourism industry has grown considerably in scale.

The second largest MSW category was paperboard with 8.49% and 8.12%, respectively, in Marrakesh area and Greater Agadir. Hotels and institutions produced a slightly high percentage of papers and newspapers. In Tunisia, Frikha et al. [19] found a similar concentration of papers in the Sousse landfill. These lower values were due to the collected paperboard by the informal recycling sector, which substantially alter this category's percentage compared with the others.

The concentration of plastics for Marrakesh area and Greater Agadir were 8.6% and 9.3%, respectively. Comparing

Table 3
Fractions generated in Marrakesh area and the Greater Agadir[a]

Waste categories	Marrakesh area[a]	Greater Agadir
	Percentage by weight (%)	Percentage by weight (%)
Organic	68.4	70.23
Paper-board	8.49	8.12
Plastics	8.6	9.3
Metals	3.12	2.54
Glass	3.01	2.21
Other	8.38	7.6

[a]A large area covering 13 municipalities that are served by the New Marrakesh controlled landfill (MNL).

the last two decades, a slight decrease of plastics was observed in 2016. This small reduction can be attributed to the implementation of environmental measures aimed at reducing plastic pollution, especially that Morocco has recently passed a new law 77–15 banning the production, sale and distribution of plastic bags.

Metals and glass were between 2.5% and 3.12% of the total MSW by weight in both regions (Marrakesh area and Greater Agadir). These lower values can also be explained by an increase of rag pickers activities. These rag pickers usually collect the materials that have good re-sale value such as metals and glass, as these materials are mostly recycled or reused [34]. The share of other waste, 8.38% and 7.6% in Marrakesh area and Greater Agadir, respectively, was also considerable, mainly consisting of debris, sanitary products and textiles.

In comparing these results with composition data from other countries, many variations and similarities can be observed in terms of waste categories percentages, particularly of organic matter. Similarly, organic waste contributes over 67% of the total MSW arriving at the landfill of Sousse in Tunisia [19]. A possible explanation for this is that the two developing countries have many common features, such as climate, population, modern living standards and the average income of the people [35]. In general, cities in Morocco such as Marrakesh and Agadir produced a high percentage of organic matter.

3.3. Leachate characterization

The most physicochemical parameters of three studied sites exceed the permissible limit values for direct discharges (Table 4).

3.3.1. pH

The average values of pH for leachate originating from MNL, MCL and GAL were 6.8, 9.1 and 8.1, respectively. The pH varies according to the age of landfills [36]. Three types of leachate according to landfill age have been defined by Alvarez and Illman [37] and Renoua et al. [10]. The new landfills have generally a low pH (<6.5); whereas mature landfills have a high pH value (>7.5); for intermediate landfill, the pH varies from 6.5 to 8. The pH values of three landfill leachates matching with the above trends. Consequently, MNC, MCL and GAL leachates could be classified as young, stabilized and intermediate, respectively. In general, pH value of old landfills (>10 years) is higher than those of young and intermediate landfills [38]. Elkadi et al. [39] found similar value (8.4) of leachate from landfill of intermediate age as compared with the GAL, while Hakkou et al. [20] reported a value ranging from 5.87 to 8.01 at MCL. This little difference in pH values could be explained by the continuous increase of pH to a steady value with the age of the landfill [40].

The relatively high pH value of MNL could be associated with the fact that this new landfill has recently undergone transition phase (transition from aerobic to anaerobic conditions) [38].

Table 4
Characteristics of raw leachate at Marrakesh (new controlled and closed) and Greater Agadir controlled landfills (MNL, MCL and GAL)

No	Parameter	Marrakesh landfills		Greater Agadir landfill	Standards
		New	Closed	Intermediate age	Discharge limit[a]
		Average	Average	Average	
1	pH	6.8 ± 0.05	9.1 ± 0.08	8.1 ± 0.04	6.5–8.5
2	Electrical conductivity (mS/cm)	66.76 ± 0.10	78.9 ± 0.06	55.43 ± 0.04	2.7
3	Suspended solids (mg/L)	1,926.93 ± 49.23	1,293.6 ± 27.75	430.05 ± 15.04	50
4	COD (mg/L)	19,523.33 ± 674.78	9,517.4 ± 375.11	14,560.7 ± 481.11	500
5	BOD (mg/L)	11,600 ± 700.31	1,756.8 ± 81.80	5,300.15 ± 253.99	100
6	BOD_5/COD	0.6 ± 0.05	0.18 ± 0.02	0.36 ± 0.04	NA
7	Total Kjeldahl nitrogen (TKN) (mg/L)	6,335.21 ± 390.84	4,026.37 ± 194.51	6,149 ± 239.12	30
8	Ammonia–N (mg/L NH_4^+–N)	5,931.25 ± 353.01	3,112.68 ± 203.47	5,226.13 ± 337.68	NA
9	Nitrate–N (mg/L NO_3–N)	35.03 ± 3.41	12.22 ± 1.34	27.47 ± 2.25	NA
10	Phenols (mg/L)	110 ± 9.53	14 ± 1.35	35.23 ± 3.17	NA

NA: Not available.
[a]*Source*: Moroccan limit values for direct discharges [72].

3.3.2. Conductivity

The conductivity values of leachate samples of the landfilling sites were, 66.76, 78.9 and 55.43 mS/cm, respectively, in MNL, MCL and GAL. The obtained values showed that leachate collected from the three landfills had high conductivity. This could be attributed to the contributions of products of the fishing industry for GAL [39] and the disposal of chemical industrial wastes containing metals for MCL over the 35-year operational period. Landfill leachate typically presents a high conductivity values that may be attributed to large amount of dissolved materials such as salts and metals [41]. The leachate at the MCL contains higher conductivity than in the others. At the MCL and GAL, relatively similar values were recorded by previous researchers 75 and 58.65 mS/cm, respectively [18,20–39]. Slightly higher values 26 and 40.92 mS/cm were recorded in Morocco and Egypt landfills, respectively [31–42]; these values remained significantly lower than those found in the present study.

3.3.3. Suspended solids

The average values of SS were 1,926.93, 1,293.6 and 430.05 mg/L, respectively, for MNL, MCL and GAL. The typical values of SS for new (less than 2 years) and old (greater than 10 years) landfills were in the range of 200 to 2,000 mg/L and 100 to 400 mg/L, respectively [43]. The average SS concentration recorded in MNL fall within the previously mentioned range. However, the value obtained at MCL was greater than those reported for old landfills. Elkadi et al. [39] found similar value 426.97 mg/L for the GAL. Greater SS value of 900 mg/L was reported at Tangier landfill leachate in Morocco by Elkadi et al. [39]. Conversely, lower SS values 28.3 mg/L than those of the present study were observed by Bakraouy et al. [44] at Oum-Azza landfill in Morocco.

3.3.4. COD and BOD_5

In this study, the highest value of COD 19,523.33 mg/L was recorded at the MNL, while the lowest value of 9,517.4 mg/L was recorded at the MCL. The obtained value from MCL leachate was high. This could be explained by the fact that the decomposition process produces new leachate continuously even though the landfill sites have been in operation for more than 10 years [40]. The COD value obtained in the GAL leachate was intermediate, with an average value of 14,560.7 mg/L. Moreover, the high COD values recorded in all three landfills could be explained by the high proportion of organic matter (68.4%–70.23% by weight) in MSW in Marrakesh area and the Greater Agadir, respectively, as mentioned, previously.

BOD_5 varies depending upon the age of the landfills [45]. The average BOD_5 values for leachate at MNL, MCL and GAL were 11,600, 1,756.8, and 5,300.15 mg/L, respectively. Tchobanoglous et al. [43] reported two different ranges as follows 2,000–30,000 mg/L and 100–200 mg/L for young and old landfill leachate, respectively. The BOD_5 staggering difference is probably due to the fact that MNL is younger than the other two landfills. The relatively high BOD_5 value was obtained at MCL and does not fall within the previously mentioned range of BOD_5 for mature landfills. Adversely, the BOD_5 value at the level of 1,756.8 mg/L was found to be higher than those reported for leachates from some aged landfill sites [46,47]. This difference could be due to the leachate recirculation, which was subjected to MCL using vertical recharge wells, spray irrigation systems and surface application.

The BOD_5/COD ratio is considered as a good indicator of degradation of organic matter in landfill [48]. In this study, the BOD_5/COD ratios for leachate at MNL, MCL and GAL were 0.6, 0.18 and 0.36, respectively. These results confirmed the previous conclusion that MNL, MCL and GAL leachates could be categorized as young, stabilized and intermediate, respectively [10]. The low BOD_5/COD ratio showed that the leachate contains a considerable amount of recalcitrant compounds such as humic and fulvic acid and thus the difficulty to be biologically degraded [10]. Assou et al. [49], found a relatively similar value of 0.16 at Mohammedia old landfill. However, BOD_5/COD ratio for MCL at the level of 0.18 was found to be higher than that reported for leachate from some old landfill site [47]. Higher BOD_5/COD ratios were recorded at MNL and GAL. Generally, this indicated the presence of organic acid, mainly composed of 80% of volatile fatty acids (VFA) and 5%–30% of VFA for young and intermediate landfills, respectively [50].

3.3.5. TKN, NH_4^+–N and NO_3^-

TKN values for landfill leachate samples were 6,335.21, 4,026.37 and 6,149 mg/L at MNL, MCL and GAL. A similar high value of 4,312 mg/L was recorded by Bakraouy et al. [44] for Oum-Azza landfill (located in Rabat, Morocco). A wider range (1,750–6,040 mg/L) was reported for a landfill leachate in Tunisia [51], which confirms the results obtained in both MCL and GAL Marrakesh closed and the Greater Agadir controlled landfill (GAL). The high nitrogen value in MCL is an indication of ammonia accumulation in leachate because there is no degradation pathway for ammonia in anaerobic phase within landfills [52].

The average values of ammonia (measured as NH_4^+–N) for MNL, MCL and GAL were 5,931.25, 3,112.68 and 5,226.13 mg/L, respectively. The leachate at the MNL contains higher ammonia concentration than in the other sites, even if this landfill is still young. This could be due to the type of waste received at landfill site from tourism industry in Marrakesh and its surrounding. Furthermore, these high concentrations may be attributed to the intensive deposition of new waste containing undecomposed nitrogenous organics [13].

According to Li and Zhao [53], ammonia in stabilized landfill leachate might vary between 3,000 and 5,000 mg/L. The ammonia concentration for leachate of MCL falls within the previously mentioned range. The higher ammonia concentration in the MCL leachate may be explained by the fermentation and hydrolysis of the nitrogenous biodegradable substrates [54]. Typically, the existence of high strengths of ammonia in landfill leachate is the primary cause of acute toxicity and is one of the most serious problems usually faced by landfill operators [55].

Nitrate values were about 35.03, 12.22 and 27.47 mg/L for leachate at MNL, MCL and AGL. Higher values of nitrate concentration in the range from 36.3 to 453.9 mg/L were recorded for leachate at Mohammedia old landfill by Assou et al. [56]. In general, the nitrate and nitrite are present in low concentrations in landfill leachate, due to denitrification in the early phase of landfill lifetime and due to anoxic conditions in the landfill, which do not allow oxidation of ammonium to nitrate and nitrite [52].

3.3.6. Phenols

The average phenol values for leachate at MNL, MCL and GAL were 14, 110 and 35.23 mg/L, respectively. In general, phenols in landfill leachates are generated throughout the degradation of the phenol-containing compounds in various types of MSW. Furthermore, phenols are considered as priority pollutants since they are toxic and dangerous for living organisms even at very low concentrations [57]. In general, the presence of phenols in the studied landfill leachates could be attributed to the disposal of olive oil production wastes, which are characterized by very high concentrations of phenolic compounds at landfill sites. Especially, that Marrakesh and Agadir regions are considered among the top olive-producing cities in Morocco.

The phenol concentrations recorded in MNL were higher than those recorded in both, MCL and GAL. The high phenol concentration in MNL may be attributed to reduction and decomposition of many of the phenolic compounds to phenol under acidogenic conditions, and to the slow degradation of phenol in anaerobic landfills [58]. Lower phenol concentration of 3.52 mg/L was recorded from the sanitary landfill site of Bizerte in Tunisia [59]. Adversely, Bakraouy et al. [44] recorded a higher value of 241.8 mg/L phenol at Rabat landfill in Morocco.

3.3.7. Heavy metal

The most common heavy metals found in landfill leachate are: cadmium, copper, nickel, chromium and lead, known by their toxicity to organisms and inhibition to biological treatment of leachate above specified threshold concentration [40]. The average concentrations of heavy metals in raw leachate at MNL, MCL and GAL are shown in Table 5. The average value of Cr for leachate collected from MNL, MCL and GAL were 0.06, 3.78 and 0.21 mg/L, respectively. The high concentration of Cr in leachate samples can be due to the disposal of chrome tannery sludge at the landfill site [60]. Higher values of 3.9 and 2.04 mg/L were recorded in another study in the landfill dump sites in Warri Metropolis in Nigeria by Godwin and Oghenekohwiroro [61] and in the landfill of the Fez city in Morocco by Khalil et al. [62], respectively. Similar values were obtained by Abd El-Salam and Abu-Zuid [42] in Egypt who found a value varying between 0.13 and 0.36 mg/L in comparison with the concentration obtained in MCL and GAL. In the leachate from MNL, MCL and GAL, the Cd concentrations were 0.14, 0.44 and 0.40 mg/L, respectively. On the other hand, the Ni concentration at MNL, MCL and GAL leachates were 0.12, 1.07 and 0.23 mg/L, respectively. A higher Ni value of 1.3 mg/L was recorded from a closed landfill located in Mavallipura landfill site in India [63].

3.4. Water balance and leachate quantity

The estimation of the annual leachate amount in the three landfills was carried out by the WBM as previously described and based on a detailed landfill sites characteristic including surface conditions and meteorological data which are given in Table 6.

The quantity of leachate generated annually was about 37,333.15, 10,054.44 and 45,558.14 m^3/annual tipping area/year in MNL, MCL and GAL, respectively (Table 7). Generally, the leachate varied significantly as the landfill age extended [54]. Even if these three landfills are not exposed to intensive precipitation as shown in Table 6, with annual amounts around 174.25 and 172.44 mm for Marrakesh and Agadir sites, respectively, a large amount of leachates were still generated. These high amounts of leachate could have been due to higher moisture content of incoming solid waste with values of 58.6%, 40.9% and 65.4% by volume, respectively, for MNL, MCL and GAL Consequently, local precipitation could be considered as a fair predictor of the leachate generation amounts based on the obtained results, especially in the low rainfall and water-deficient areas in Morocco. The influence on leachate generation in semi-arid climate of moisture content of the MSW was confirmed by another study conducted by Aljaradin and Persson [18]. Given the fact that the amount of leachate depend upon many factors, among others, the characteristics of the waste, the design and operation of the landfill and the climatic conditions, it is difficult to make a direct comparison between the leachate

Table 5
Heavy metal concentration in raw leachate at Marrakesh (new controlled and closed) and Greater Agadir controlled landfills (MN, MCL and GAL)

No	Parameter	Marrakesh landfills		Greater Agadir landfill	Standard
		New	Closed	Intermediate age	Discharge limit[a]
		Average	Average	Average	
1	Cr T (mg/L)	0.06 ± 0.01	3.78 ± 0.33	0.21 ± 0.02	2
2	Ni (mg/L)	0.12 ± 0.01	1.07 ± 0.15	0.23 ± 0.01	0.5
3	Zn (mg/L)	0.17 ± 0.02	1.95 ± 0.13	0.21 ± 0.02	5
4	Pb (mg/L)	0.19 ± 0.02	0.23 ± 0.01	0.08 ± 0.01	0.5

**Source*: Moroccan Limit values for direct discharges [72].

Table 6
Summary of water balance calculations

Parameters (mm)	Marrakesh		Agadir
	New	Closed	Greater Agadir landfill
Annual precipitation	174.25	174.25	172.44
Volumetric moisture content[a]	586.50	409.50	654.50
Infiltrate deep drainage	0.00	120.00	0.00
Evaporation	149.86	149.86	148.29
Leachate volume (m^3/year)	37,333.15	10,054.44	45,558.14

[a]mm of water per m of refuse.

Table 7
Theoretical leachate annual generation volumes

Parameters	Marrakesh		Agadir
	New	Closed	Greater Agadir landfill
Depth of fill (m)	4.50	6.00	5.00
Annual tipping area/year (ha)	1.90	1.20	1.80
Leachate generation volume/year (m^3)	37,333.15	10,054.44	45,558.14

volumes obtained from the three landfills covered in this study and those found in the literature. Apart from its effect on leachate generation, high moisture content plays a significant role in the biochemical processes and the distribution of nutrients and microorganisms within the landfill [64]. Moreover, Yang et al. [65] indicated that the moisture content of incoming fresh waste present during compaction would aid in compaction to obtain a denser fill and to get a maximum amount of waste placement in a given landfill volume. Leachate volume generation at a landfill site is irregular but dependent on many factors; in general, it is determined by the following four conditions, which can be described as follows: availability of water, landfill surface conditions, refuse and underlying conditions [19]. The primary factors affecting the availability of water and the refuse conditions in landfills for semi-arid regions are the moisture content, the kind of refuse compaction and landfill age [19].

Based on the above factors affecting leachate generation, Ehring [66] stated that production from young landfill is minor. This statement is based upon the fact that the field capacity of given solid waste level must be reached before any significant leachate would be generated, as pointed out in the previous section. However, it can be observed that the annual leachate amount (37,333.15 m^3/annual tipping area/year) calculated from WBM in MNL was higher than that produced generally in a young landfill with fresh deposits. This may indicate the presence of large and more or less continuous voids, termed as macropores within a landfill resulting from the heterogeneous nature of solid waste [67]. Macropores are the main factors for the appearance of preferential flow in young deposits. For this reason, the existence of preferential flow is believed to be the primary reason why existing leachate prediction models are not in agreement with actual field measurements and observations [68]. On the other hand, the discharge from MCL is the lowest (10,054.44 m^3/annual tipping area/year) compared with the two other landfills. This could be due to the fact that covering and planting operations are currently in progress. Generally, the final cover installation increases response of the discharge from the old landfill to the surface processes and consequently results in a decrease in the final volume of leachate produced [69,70]. Hence, the site owner need to develop and evaluate strategies for managing leachate generation that will occur after the end of the post closure monitoring period, especially in sites, such as the MCL, where there was no natural liner to prevent the leakage of leachate to groundwater.

The GAL also produced annually a significantly greater leachate volume of about 45,558.14 m^3/annual tipping area/year. This could be explained by the fact that the macropore flow is not significant due to the superposition of well-compacted layers of daily cover [14]. In other words, the percolation through the refuse deposits, saturated to near field capacity, occurs mainly as matrix flow [71].

4. Conclusion

This study carried out a quantitative and qualitative analysis of the various types of leachates likely to be produced in Morocco under semi-arid climate from three landfill sites with different ages and waste types. The organic matter over 68% is the most dominant fraction. The annual generated leachate volume from each landfill site was estimated using a WBM, which is more adaptable to the semi-arid climate. The leachate amount was approximately 37,333.15, 10,054.44 and 45,558.14 m^3/annual tipping area/year, for leachate at MNL, MCL and AGL Marrakesh. The landfill leachate physico-chemical characterization showed that the recorded values were still high according to Moroccan direct discharge standards such as COD 19,523.33, 9,517.4 and 14,560.7 mg/L; BOD_5 11,600, 1,756.8 and 5,300.15 mg/L, respectively, for MNL, MCL and AGL. MCL and GAL sites demonstrated low biodegradability, that is, $BOD_5/COD = 0.18$ and $BOD_5/COD = 0.36$ compared with MNL site, that is, $BOD_5/COD = 0.6$. The high concentration of Cr of approximately 3.78 mg/L was recorded in leachate from MCL. It was concluded that leachate is still generated in landfills located in a semi-arid area even with a low annual precipitation, due to the high moisture content of MSW. This latter factor was considered as the key leachate-generating component in semi-arid countries. Thus, the studied leachates require an accurate estimate of the leachate quantity and a suitable technique for treatment to reduce the pollutants to an acceptable level prior to discharge into receiving water bodies.

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